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ABSTRACT

The impressive rate of particle loss by vertical beat-frequency (VBF) blowup in the low electrical field of a synchrocyclotron suggests the application of a radiofrequency perturbation to induce growth of radial oscillation amplitude for beam extraction. The use of an electrical field with a linear gradient on the outward side of a reference orbit and extending 60° in azimuth has been studied. The radiofrequency is chosen to make radial oscillations, described by an equation of the Hill type, unstable. Orbit calculations for a cyclotron with 50-Mev deuterons in a 17,000-gauss field have been made on a digital computer. Two essential features were observed: (a) a reasonable separation between successive turns influenced by the perturbation, and (b) a phasing of orbits so that the maxima following an increase in amplitude occur near one azimuth. An electrical gradient of 4.3 kv/cm^2 was used in the computations. The application of this system to variable-energy constant-frequency cyclotrons and very-high-energy accelerators is under study. The possibility of changing the electrical frequency and gradient to match operating conditions eliminates difficulties arising in magnetic extraction systems for variable-energy machines.

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I. INTRODUCTION

In experiments involving beam storage in the 184-inch cyclotron, a mechanism was observed which effectively increased the particles' vertical amplitude and quickly destroyed the beam.[1] The process, called vertical beat-frequency (VBF) loss, occurs when the frequency of axial oscillation is related to the rotational frequency of the particles in the cyclotron and the frequency of the accelerating voltage of the cyclotron. The relationship is given in the following equation:

$$f_z = f - f_0,$$

where f_z equals $\sqrt{n}\, f_0$, f_0 is the rotational frequency of the particle, f is the frequency of the cyclotron oscillator, and n is the conventional cyclotron magnetic field parameter. The relation

$$f = f_0 (\sqrt{n} + 1)$$

is one required condition for this process to occur, while the other necessary condition is that there be a vertical electric field which is proportional to the vertical displacement of the particle from the midplane of the cyclotron. In the weak vertical field component of the accelerating voltage in the 184-inch cyclotron the beam loss was impressively fast. An analysis shows that under these two conditions the equation of particle motion is absolutely unstable. The application of a similar set of conditions for the radial motion of a particle at the outer radii of the cyclotron is suggested as a means of extracting particles from a cyclotron.

Computations on the IBM 650 have been undertaken to determine the possibilities of this method of extraction. The study of a deflecting system

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for a variable-energy constant-frequency (VECF) cyclotron is of interest. This cyclotron is envisioned as accelerating deuterons to about 50 Mev in about a 17,000 gauss field. However, the initial computations apply to a conventional cyclotron which has a magnetic field decreasing with radius. In order to use the parameters which have been suggested for the VECF cyclotron, we have selected a 50-Mev deuteron at 33.7-in. radius. We have also chosen $n = 1/10$. While this is rather artificial, it nevertheless does provide a test of the rf field strength required to perturb the particles, and it will suggest a number of features of the perturbed orbits.

In the conventional cyclotron, the linearized equation for radial oscillation about a reference orbit is

$$\frac{d^2\rho}{dt^2} + (1-n)\,\omega_0^2\,\rho = 0, \tag{1}$$

where ρ is the departure from a synchronous orbit.

We introduce as a perturbing force a sinusoidal electrical variation which is proportional to the outward displacement from the synchronous orbit. We have chosen an azimuthal extent of 60° and a linear gradient. The perturbation has the form

$$F = A\rho \cos \omega t$$

for $\rho > 0$ in region of perturbation, and

$$F = 0$$

for all other regions.

We change variables and obtain

$$\frac{d^2\rho}{d\phi^2} + \left[\frac{4\,\omega_0^2(1-n)}{\omega^2} - \frac{4A}{\omega^2}\cos 2\phi\right]\rho = 0 \tag{2}$$

for $\rho > 0$ in region of perturbation, or

$$\frac{d^2\rho}{d\phi^2} + \left[\frac{4\omega_0^2\,(1-n)}{\omega^2}\right]\rho = 0 \tag{3}$$

elsewhere.

II. CONDITIONS FOR INSTABILITY IN RADIAL MOTION

An examination of Eqs. (2) and (3) shows that the particle motion is unstable when $A \neq 0$ and if ω is chosen so that the first term in the bracket of Eq. (2) equals ℓ^2, where $\ell = 1, 2, 3, \ldots$. The frequencies of the perturbing radial voltage that will result in an absolute instability in the radial equation of motion are tabulated below for a conventional cyclotron.

$$\begin{aligned} \omega &= \omega_0 \sqrt{1-n} \;\; 2 && \text{for } \ell = 1 \\ &= \omega_0 \sqrt{1-n} && \ell = 2 \\ &= \omega_0 \sqrt{1-n} \;\; 2/3 && \ell = 3 \\ &\;\;\vdots && \end{aligned}$$

It is an advantage to choose the smallest value of ℓ, since the choice allows the least sensitivity in matching the perturbing frequency to the particle motion. This is useful in the case where the radial oscillation frequency changes owing to a rapidly changing edge field of the cyclotron.

III. THE SYSTEM CHOSEN FOR PRELIMINARY STUDY

The radial motion of 50-Mev deuterons in a 17-kilogauss magnetic field of a conventional cyclotron was calculated by integrations of the radial and azimuthal component equations of the Lorentz equation. The axial motion was disregarded. The equations are:

$$\frac{d^2 r}{d\tau^2} = r \frac{d\theta}{d\tau} \left[\beta_z + \frac{d\theta}{d\tau} \right] + \epsilon \left[r - r_0 \right] \cos 2\phi \qquad (4)$$

$$\frac{d^2 \theta}{d\tau^2} = - \frac{1}{r} \frac{dr}{d\tau} \left[\beta_z + 2 \frac{d\theta}{d\tau} \right], \qquad (5)$$

where $\epsilon = 0$ except in perturbation region, $\phi = \sqrt{1-n}\;\tau$, and $\beta = B_z/B_0$.

The magnetic field is given in general by:

$$B_z = B_0 \left(\frac{r}{r_0} \right)^k (1 + f \cos N\theta). \qquad (6)$$

In these calculations we used the following values:

B_0 = 17,000 gauss
r_0 = 33.68 inches
k = -0.1 (n = 0.1)
f = 0.

The amplitude of the perturbing force is related to the terms in Eqs. (2), (3), and (4) by

$$\frac{A}{\omega_0^2 (1-n)} = \frac{eE}{M\gamma\omega_0^2 (1-n)} = \epsilon ,$$

where we use $E \cong 4.3$ kv/cm^2 as the electrical gradient. $M\gamma$ is the relativistic mass of the deuteron. This rf electrical-field gradient, less than 5 kv/cm^2, is believed to be easily obtainable by an oscillator which is independent of the cyclotron oscillator and which can be tuned to the optimum frequency and amplitude.

IV. FEATURES OF ORBITS CALCULATED ON THE IBM 650 FOR THE PRELIMINARY EXAMPLE

Calculations on the IBM 650 have been done in the median plane only. The perturbation is introduced when the particle is beyond the synchronous radius in a region from 100° to 160°. An initial azimuth of 0° is assumed for all the orbits that have been examined. Starting phases of 0, 60, 120, 180, 240 and 300 degrees have been used.

Unperturbed orbits with radial oscillations were examined and their periods checked to see that the solution matched the expected performance. Later, particles which initially had a radial oscillation amplitude up to 1/2 in. were examined with the various starting phases. The interval of integration was chosen to be about 1/10 of one radian, except that in the region where the perturbation occurred, about 1/5 of this value was used.

The results of the orbit computations confirm the expectation that the rf perturbation would be effective in changing the radial oscillation amplitudes. Of great interest is the amount of radial amplitude increase between adjacent turns and the amount of preferential orientation of orbits in the reference frame of the cyclotron. Preferential orientation means that maxima of the radial oscillation occur repeatedly or at least quasi-repeatedly near one azimuth. A substantial increase in amplitude between successive turns would allow the introduction of a channel or a deflecting system to separate the extracted particles from the circulating particles. In the case of a Thomas machine, "falling over the edge of a hill" may be employed if the deflecting system is placed so that the maxima occur at a given hill. The advantage of this technique was demonstrated in an electron model of the Thomas machine at this Laboratory in 1952.[2]

A possible arrangement of the system is shown in Fig. 1. In Fig. 2 we have plotted the amplitude versus the azimuthal position at which the maxima occur. An impressive change in amplitude has been observed between successive turns in the region immediately following the perturbation. These orbits have an outward excursion in the perturbation region. However, orbits precess and after a few influential encounters with the perturbation, the particles tend to miss it altogether. For several turns the amplitude remains almost unchanged and the maxima occur farther around the cyclotron. Later another series of changes in amplitude takes place.

Several orbits made a number of turns before precessing into the perturbation. Some orbits had their amplitudes decreased substantially by the perturbation, but because of the precession of orbits all particles are ultimately perturbed to large radial oscillation amplitudes.

V. THE ACTION OF THE PERTURBATION ON HIGHER ENERGY PARTICLES

The effect of perturbation upon higher energy particles was computed for particles with a synchronous radius 1/2 in. larger than the synchronous radius used in the calculations of Sec. IV. These orbits represent particles whose energy (51.5 Mev) is somewhat larger than the design energy for Sec. IV. The synchronous radius passes through the perturbation.

Initial conditions have been chosen for particles with 1/2 in. of oscillation amplitude about the new synchronous orbit. A particle on a synchronous orbit (no oscillation amplitude) was also computed for this higher energy case. All the orbits show that the perturbation causes their amplitudes to grow after a sufficient number of turns. The general features of the orbits are very much like those described in Sec. IV. The orbits, on the average, are deeper into the perturbation than in the previous case, with the result that the average amplitude change per turn is much greater than in Sec. IV. Figure 3 shows ten turns of a perturbed orbit. Figure 4 shows the maxima vs azimuthal position for several initial phases of orbits with 0.5-in. initial amplitude. Particles which gain enough energy per turn to make a substantial change in radius in a few turns will approximate the conditions of this case.

The particle with no initial oscillation amplitude was made to oscillate immediately by the perturbation. Inspection of Fig. 3 shows that the perturbation does not appear to divert the orbit abruptly; however, the result of a number of passes through the perturbation is a large increase in oscillation amplitude.

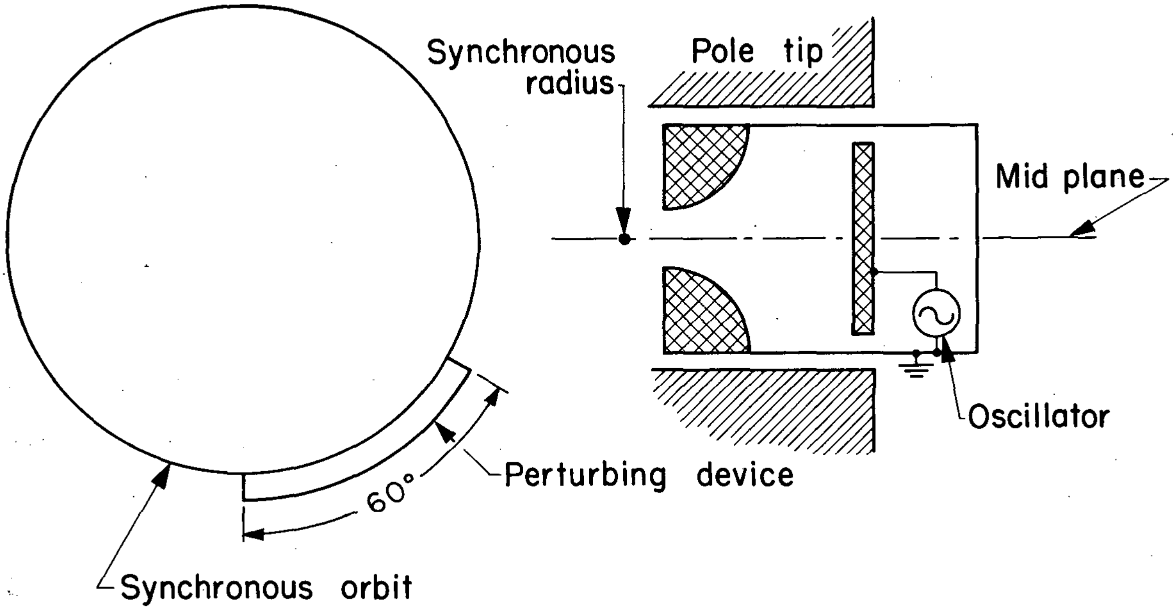

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Fig. 1. Arrangement of the perturbing system. Two parabolic and one flat electrode provide a linearily increasing rf field.

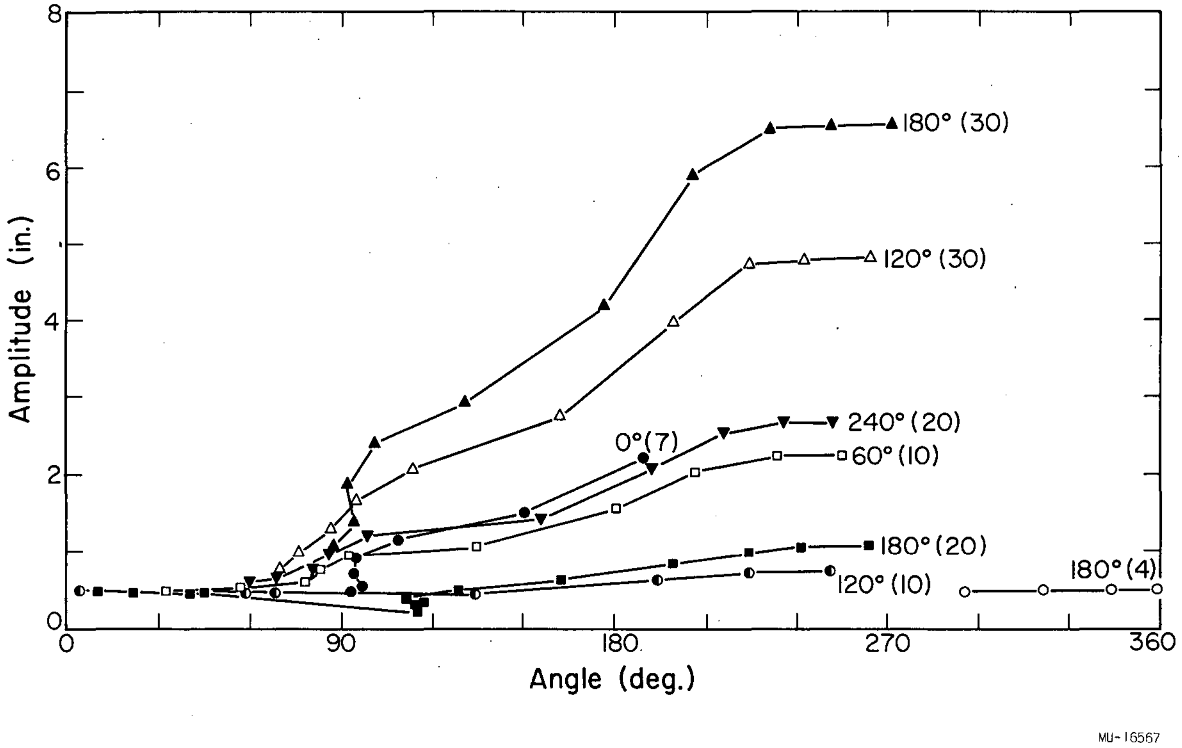

Fig. 2. Location of maxima of radial amplitude vs azimuth. The notation 180° (30) designates the maximum point in the 30th turn of the orbit with an initial phase angle of 180°. The line connects maxima of consecutive previous turns. The initial **oscillation amplitude is 0.5 in. for all orbits.**

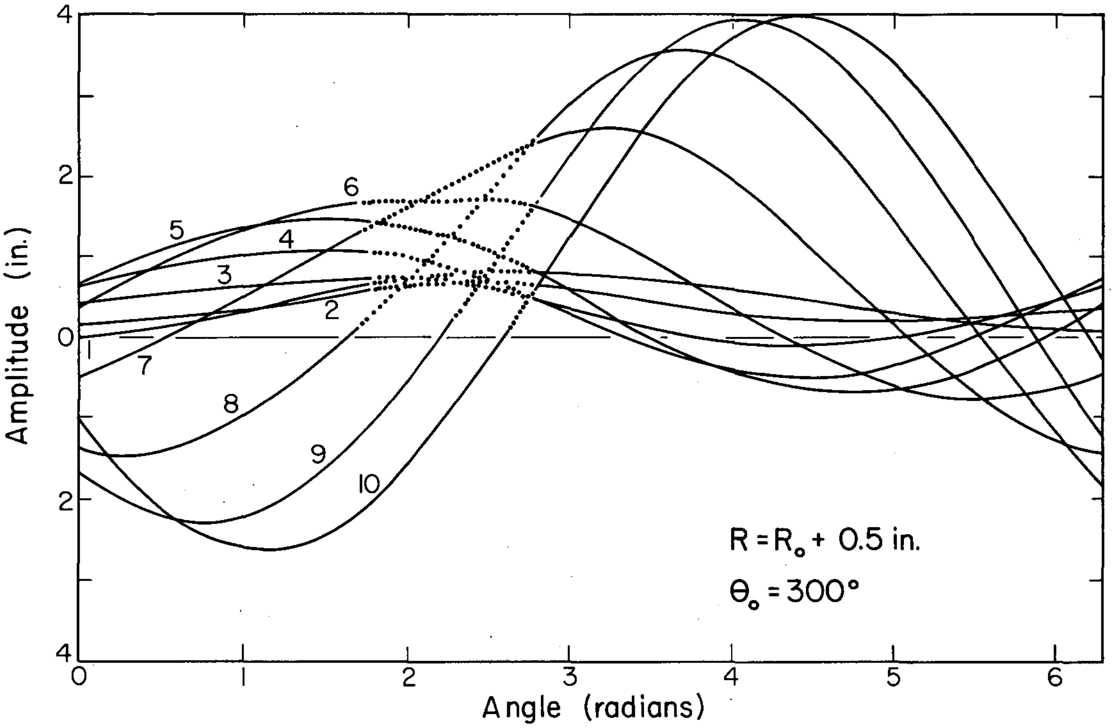

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Fig. 3. Ten consecutive orbits experiencing the perturbation. Amplitude change and precession through the perturbation region are observed. Departure from the synchronous orbit is plotted against azimuthal position in the cyclotron. An initial phase of 300° is used for 0.5-in. oscillation about a synchronous radius 0.5 in. larger than the start of the perturbation. The dots represent points in the integrated orbits where the perturbation is applied.

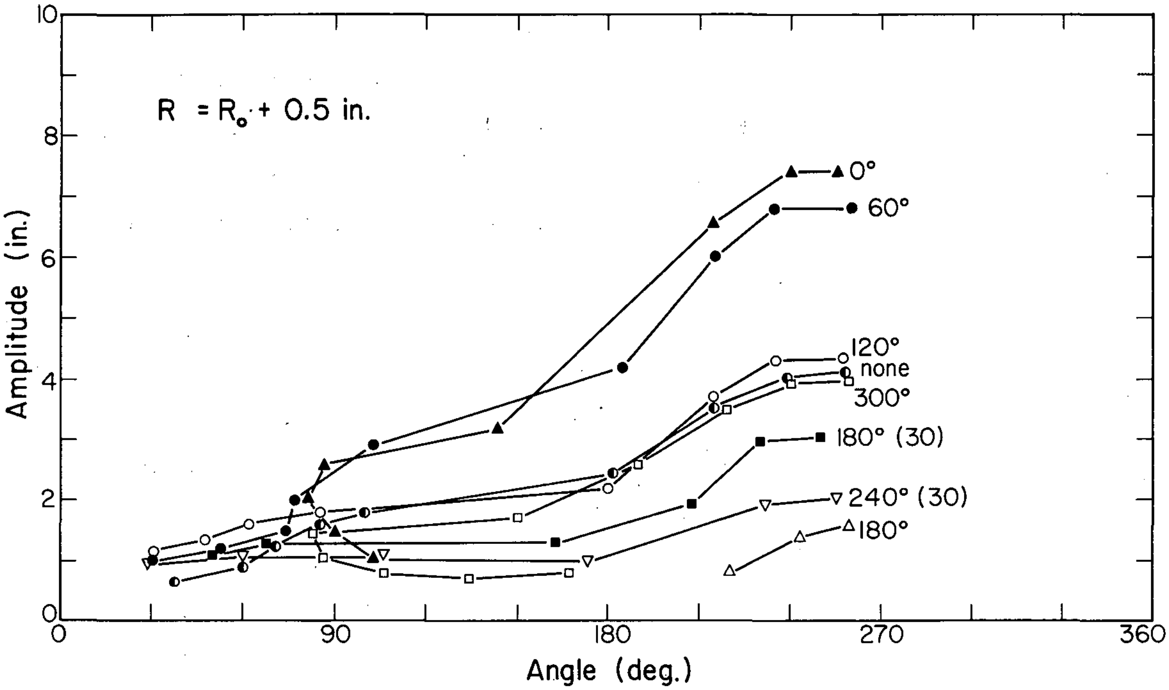

Fig. 4. Location of maxima of radial amplitude vs azimuth for the higher energy particles. The notation is the same as for Figure 2. The marked point is for the tenth turn unless otherwise specified. The point designated "none" is for a particle started on a synchronous orbit, no oscillation amplitude initially.

V. FURTHER INVESTIGATIONS

The calculation of orbits, where k in Eq. (6) is chosen to be 0.048, has been made preparatory to the study of orbits in a sinusoidal Thomas-type cyclotron. The orbits in the increasing fields precess in the opposite sense to the previously considered orbits as they oscillate about the circular ($f = 0$ in Eq. (6)) synchronous orbit. Under the influence of the perturbation, whose frequency was obtained from $\phi = \sqrt{1+k}\,\tau$, the orbits experience a change in amplitude. A typical orbit of a 50-Mev deuteron is shown in Fig. 5.

The computation of orbits in a sinusoidal Thomas-type cyclotron ($f = 0.2$, $k = 0.048$, $N = 4$) is being continued.

The influence of a radiofrequency perturbation on orbits of very-high-energy accelerators is of interest. An increase in radial amplitude may be useful either for extracting particles from the accelerator or causing the particles to strike an internal target without the energy loss which occurs in the lip-edged targets that are commonly used.

ACKNOWLEDGMENT

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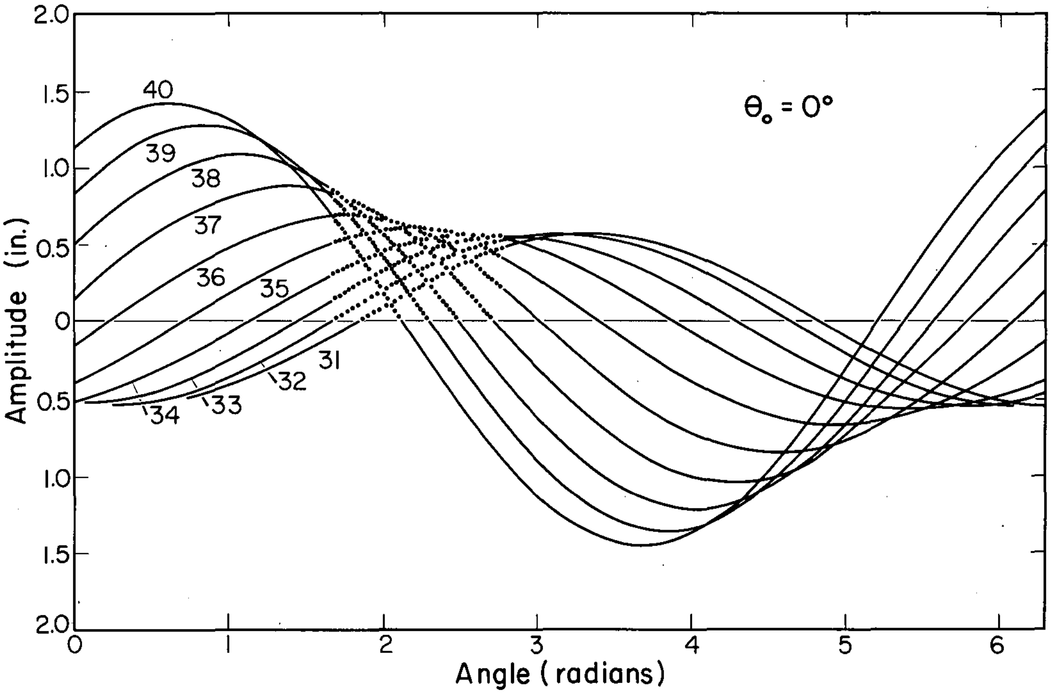

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Fig. 5. Ten consecutive turns experiencing the perturbation. Oscillations are about a circular synchronous orbit in a magnetic field increasing with radius; k = 0.048 and f = 0 in Eq. (6), with an initial amplitude of 0.5 in. and phase of 0 degrees. Crosses indicate region of perturbation. The synchronous energy of the **deuteron is** 50 Mev.

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